Schistosome Infection of Transgenic Mice Defines Distinct and Contrasting Pathogenic Roles for IL-4 and IL-13: IL-13 Is a Profibrotic Agent[1]

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Experimental *Schistosoma mansoni* infections of mice lead to a dynamic type 2 cytokine-mediated pathological process. We have used IL-4-deficient, IL-13-deficient, and IL-4/13-deficient mice to dissect the role of these cytokines in the development of immune response and pathology following *S. mansoni* infection. We demonstrate that while both of these cytokines are necessary to develop a robust Th2 cell-driven, eosinophil-rich granuloma response, they also perform disparate functions that identify novel sites for therapeutic intervention. IL-13-deficient mice demonstrated significantly enhanced survival following infection, which correlated with reduced hepatic fibrosis. In contrast, increased mortality was manifest in IL-4-deficient and IL-4/13-deficient mice, and this correlated with hepatocyte damage and intestinal pathology. Therefore, we demonstrate that during a dynamic type 2 cytokine disease process IL-13 is detrimental to survival following infection, whereas IL-4 is beneficial. ***The Journal of Immunology*****, 2000, 164: 2585–2591.**

A defining feature of the pathologies of a number of human diseases is an elevated type 2 cytokine (IL-4, IL-5, IL-10, IL-13) phenotype and concurrent reduction in type 1 cytokine (IFN-γ, IL-2) responses. A type 2 cytokine response is characterized by increased (Th2) cell development (production of IL-4 and IL-5) resulting in IgE production and eosinophilia. Type 2 cytokine responses are causally associated with allergies, asthma, and helminth infections (1). During the last decade, IL-4 has been proposed as the key regulatory molecule for Th2 cell differentiation and type 2 cytokine responses (2). More recently, IL-13 has been implicated as a central mediator in certain Th2-cytokine pathologies (3–7). IL-13 shares 30% homology with IL-4 and appears to have certain overlapping biological activities (8). This overlap in biological activity is due to IL-4 and IL-13 using the IL-4 receptor α-chain (IL-4Rα) as a component of their receptor complexes (9) and signal through a shared STAT6-dependent pathway (10). Both cytokines have been demonstrated to modulate IgE expression (11, 12), the development of type 2 cytokine responses (13, 14), and the suppression of inflammatory cytokine production from monocytes (15, 16). Indeed, recent experiments have shown that IL-4 and IL-13 may perform additive roles in type 2 cytokine responses (14). However, it is clear that these cytokines also have distinct biological roles. IL-4 directly induces T cell proliferation and differentiation (2, 17, 18), whilst IL-13 probably mediates its effects on T cells indirectly (13). In contrast, studies using gastrointestinal helminth parasite infections have identified that IL-13 plays a more dominant role in the expulsion of certain worm infections (5–7, 19).

A number of recent studies have used the synchronous schistosome egg pulmonary granuloma model to elucidate the relative roles of IL-4 and IL-13 in the formation of the schistosome granuloma. In this model, schistosome eggs elicit pulmonary granulomas after i.v. injection of eggs into naive or egg-sensitized mice (20). Using cytokine-deficient mice, we have shown that the pulmonary granulomatous inflammation is partially impaired in IL-4- or IL-13-deficient mice; with a reduction in pulmonary eosinophil infiltration and IgE and Th2 (IL-5, IL-10) production relative to wild-type animals (14). In contrast, these responses were abolished in combined IL-4/IL-13-deficient mice, with a type 1 (IFN-γ) dominated response (14). Similar findings were observed following blocking IL-13 activity in IL-4-deficient mice with a soluble IL-13R α2-Fc fusion protein (21).

Studies to date employing IL-4-, STAT6-, or IL-4Rα-deficient mice have suggested IL-13 may have a role in IL-4-independent responses during helminth infections (7, 19, 22, 23). It has been observed that a caveat in these models is that the biological phenotype observed can only be surmised to be solely due to IL-13, with other, possible unknown, factors having a potential role (24). With respect to murine schistosomiasis, a potential role for IL-13 in granuloma formation and fibrosis was implied by early studies in IL-4Rα-deficient mice (23), and, more recently, a direct role for IL-13 was shown by blocking IL-13 activity (25). In this study, the availability of IL-4-alone, IL-13-alone, and both IL-4 and IL-13 cytokine gene-targeted mouse lines has permitted the intimate dissection of the direct role of IL-13 in a type 2 cytokine-mediated infection. This study demonstrates that removal of IL-13 from the Th2 cytokine response to *Schistosoma mansoni* infection is beneficial to host survival. This enhanced prognosis correlates with a reduction in collagen deposition and indicates a novel role for IL-13 in the development of hepatic fibrosis. By contrast, we also show that removal of IL-4 results in very high mortality characterized by a breakdown in intestinal integrity and the development

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of endotoxemia; implicating IL-4 as a protective cytokine in schistosome infection. The combined removal of both IL-4 and IL-13 demonstrated that the positive effects resulting from the ablation of IL-13 were over-ridden by the detrimental pathology resulting from IL-4 removal. Moreover, combined cytokine deletion resulted in a phenotype that was considerably more severe and deleterious than that observed in the IL-4-deficient line. These data identify the potential benefits of targeting IL-13 removal, but also highlight the dangers of blocking both IL-13 and IL-4 concurrently.

Materials and Methods

Mice and parasitology

The preparation of IL-4 (26), IL-13 (13) and IL-4/13 (14) gene-targeted mice has been described. All animals had been back-crossed on a BALB/c background at least four times. Animals were housed under standard conditions in a specific pathogen free facility. A Puerto Rican strain of *S. mansoni* was used for all experiments. Six- to 8 wk-old female mice were percutaneously infected with *S. mansoni* (27). In three separate experiments, mice were acutely infected (exposure to 100 cercariae) for 8 wk. In all acute infections, 6–12 mice were used per group. In separate studies, IL-13$^{-/-}$, IL-4/13$^{-/-}$, and homozygous (+/+) litter-mates on a 129 $\times$ C57BL/6 (F_2) background were chronically infected (exposure to 25 cercariae) for 16 wk. For chronic infections, 14–15 mice were infected per group. Portal perfusion for worm counts, digestion of tissue for egg counts, and fecal egg counts were as described (27, 28).

During the infection, the body weights of all mice were monitored. In compliance with U.K. Home Office Licence legislation, animals that developed severe overt morbidity during infection were humanely killed.

Pathology studies

The methods used for measurement of pathological parameters have been described (29). In brief, liver or intestinal sections were stained with hematoxylin and eosin for granuloma diameter measurement, Giemsa-stained for eosinophil counts, or stained with Martius Scarlet Blue for examination of tissue fibrosis. All histological samples (histology slides, plasma) were numerically coded before analysis. The same individual measured all pathological parameters blind. The diameters of the granuloma surrounding individual eggs were measured using an ocular micrometer. For each mouse, the diameters of at least 21 individual egg granulomas were measured, with 6–12 mice examined (minimum of 126 individual granulomas measured per group in each of three separate experiments). The volume of the granuloma was calculated assuming a spherical shape. Tissue collagen in the livers of uninfected and infected mice was quantified by differential staining of sections (three per mouse) on slides and was expressed as the increase in hepatic collagen, micrograms of collagen per milligram of protein. To determine hepatocyte damage, plasma aspartate aminotransferase levels were assayed (Sigma, Dorset, U.K.). LPS was measured in plasma using a commercial kit (COATEST Plasma-Endotoxin; Chromogenic AB, Molndal, Sweden); plasma samples were diluted in endotoxin-free water and assayed according to the manufacturers instructions. Intestinal eosinophilia was determined using the eosinophil peroxidase assay, essentially as described (30). The numbers of eosinophils (expressed as 10^6 per gram of tissue) were interpolated from a standard curve prepared from eosinophils purified from the blood of *Nippostrongylus braziliensis*-infected mice.

Immunological assays

Animals were sacrificed on day 45 after infection, before substantial deaths in IL-4- and IL-4/13-deficient mice, for analysis of their immune responses. Plasma and blood were recovered. The spleen and mesenteric lymph node cells were aseptically removed. Single-cell suspensions were prepared as described (31). Cells (5×10^6/ml) were stimulated with parasite egg Ags (10 μg/ml) or *Escherichia coli* LPS serotype 0127:B8 (1 μg/ml; Sigma). IL-4, IL-5, IL-10, IL-13, TNF-α, and IFN-γ were detected in culture supernatants by ELISA as described previously (14, 29). The Griess reaction (32) was used to quantify nitrite levels in the supernatants of cell cultures. Lamina propria cells were isolated from the ileum of infected mice using standard techniques (33). Cells recovered from the ileums of two individual mice were pooled and restimulated in vitro with Con A (25 μg/ml) for 8 h with Brefeldin A (5 μg/ml) added for the last 3 h of culture. Surface staining of lamina propria CD4$^+$ T cells, intracellular IL-5, or IFN-γ staining and subsequent FACS analysis were as reported previously (31). Analysis of parasite Ag-specific Ab responses were as described (29).

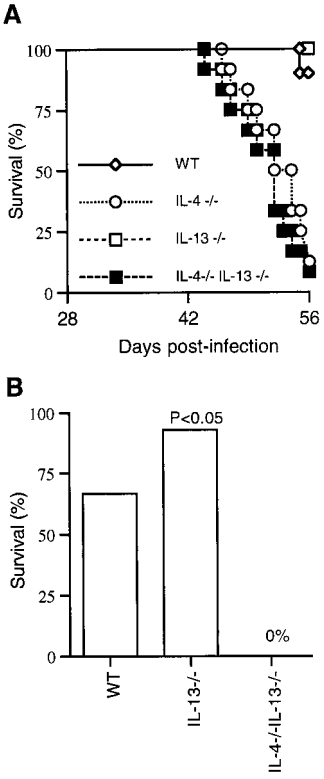

FIGURE 1. Mortalities of IL-4-deficient, IL-13-deficient, IL-4/13-deficient, and wild-type mice during *S. mansoni* infection. *A*, Mice were acutely infected with 100 *S. mansoni* cercariae, and mortalities were monitored until week 8 after infection. There was no statistical difference in the mortalities of IL-4-deficient or IL-4/13-deficient groups. IL-13-deficient mice had significantly fewer mortalities during an acute infection than wild-type mice ($p < 0.05$). Eleven to 14 mice were infected per group, and data are representative of three separate experiments. *B*, Following a chronic infection (25 cercariae), mortalities were followed until 16 wk postinfection. Fourteen to 15 mice were used per group. There was significantly greater ($p < 0.05$) survival of IL-13-deficient mice relative to wild-type animals.

Statistical analysis

Data from individual mice are presented as the group mean $\pm$ SD or SEM, as indicated. Statistical differences between groups was determined using ANOVA, and post hoc comparisons were done with Dunnett's test. Differences between survival of mice were analyzed by Kruskal-Wallis test of ranked survival times. Values of $p < 0.05$ were considered significant.

Results

IL-13 deficiency enhances survival, while IL-4 deficiency induces mortality during schistosome infection

Following acute infection with *S. mansoni* (exposure to 100 cercariae), significant mortality was observed in the IL-4$^{-/-}$ and IL-4/13-deficient mice, with >80% expiration by day 56 (Fig. 1*A*). Death was preceded by progressive weight loss and cachexia (data not shown). In marked contrast, there were considerably fewer mortalities in wild-type animals (13%) and no deaths in the IL-13$^{-/-}$ mice (Fig. 1*A*). In three separate acute infections, IL-13$^{-/-}$ mice had significantly lower mortalities than wild-type animals ($p < 0.05$). A similar mortality profile was observed when animals were subjected to a chronic (exposure to 25 cercariae) infection (Fig. 1*B*). All IL-4/13-deficient mice (100% mortality) died by

Table I. *Parasitological data in* S. mansoni*-infected wild-type, IL-13-deficient, IL-4-deficient, and IL-4/13-deficient mice*[a]

Group (no. of mice)	Worm Pairs	Fecundity (eggs/worm pair $\times 10^{-3}$)	Tissue Eggs ($\times 10^{-3}$)	
			Liver	Intestine
Wild type (7)	15.1 ± 1.9	3.9 ± 0.4	21.5 ± 1.8	33.8 ± 3.4
IL-13$^{-/-}$ (6)	15.4 ± 2.5	4.2 ± 0.5	21.2 ± 0.8	34.9 ± 2.8
IL-4$^{-/-}$ (6)	14.9 ± 1.8	4.8 ± 0.4	20.1 ± 0.8	48.5 ± 4.8[b]
IL-4/IL-13$^{-/-}$ (7)	15.3 ± 1.3	4.7 ± 0.3	21.2 ± 1.1	51.5 ± 6.1[b]

[a] Data are presented as mean and SEM and are representative of three separate acute infections.
[b] Significantly more eggs ($p < 0.05$) in the intestines of IL-4- and IL-4/13-deficient mice compared to wild-type and IL-13-deficient mice. Analysis by ANOVA and Dunnets tests.

week 10, whereas by 16 wk of infection significantly fewer wild-type mice (36% mortality) and still fewer IL-13$^{-/-}$ mice (7% mortality) had expired ($p < 0.05$; $n = 14$–15 mice per group). Determination of parasite worm burdens and parasite fecundity demonstrated that the differences in mortality between groups were not simply due to variation in infectivity or fecundity of the parasite between the mouse lines (Table I). These data demonstrate that the absence of IL-13 was beneficial for infected animals, with IL-13$^{-/-}$ mice surviving longer than wild-type animals. Conversely, deficiency in IL-4 results in increased mortality, suggesting that IL-4, or IL-4-dependent responses, have a protective role in infection.

Granuloma formation and eosinophil infiltration are abrogated only in the combined absence of IL-4 and IL-13

During schistosome infection, the liver is the major organ affected, with eggs trapped in the liver parenchyma evoking type 2 cytokine-dependent granulomatous inflammation. This is characterized by the presence of numerous infiltrating eosinophils, but also by the deposition of collagen and a resultant fibrotic lesion. Histological analysis identified that while wild-type, IL-4$^{-/-}$, and IL-13$^{-/-}$ mice had comparable hepatic granuloma formation, there was a striking reduction in granuloma development in the IL-4/13-deficient mice (Fig. 2*a* and Fig. 3*A*). Additionally, granulomas from the IL-4/13-deficient animals were virtually devoid of the characteristic eosinophil infiltration present in the granulomas of the other mouse lines (Fig. 3*B*). Instead, the limited granuloma response from the IL-4/13-deficient animals was comprised of macrophages (data not shown).

Fibrosis is significantly diminished in the absence of IL-13

Because hepatic fibrosis is a major clinical manifestation of schistosomiasis, we examined collagen deposition in the livers of infected mice. Histological analysis and collagen quantification identified that there was negligible hepatic fibrosis in the IL-13-deficient or IL-4/13-deficient mice when compared with wild-type or IL-4-deficient mice (Fig. 2*b* and Fig. 3*C*). Although schistosome-infected mice do not develop portal fibrosis to the same extent as schistosome-infected humans (34), it is noteworthy that IL-4/13-deficient mice also displayed reduced periportal fibrosis compared with the collagen deposition in wild-type animals (Fig. 2*b*).

IL-4 protects against liver damage

To determine whether the alterations in the liver pathology generated in the different mouse strains affected hepatocyte integrity, we measured plasma aspartate aminotransferase levels as an indicator of cell damage. IL-13-deficient mice had similar transaminase levels to wild-type mice (Fig. 3*D*). In contrast, although IL-4-deficient mice demonstrated normal granulomatous responses, these animals had ~5-fold greater levels of circulating transaminase than wild-type mice. Hepatocyte damage was even more markedly exacerbated in IL-4/13-deficient mice, with transaminase levels 10-fold higher than wild-type mice (Fig. 3*D*). Elevated plasma transaminase levels and impaired hepatic granuloma responses in schistosome-infected mice have been associated with steatohepatitis and extensive microvesicular steatosis (29, 35). However, there was no microvesicular damage in IL-4/13-deficient

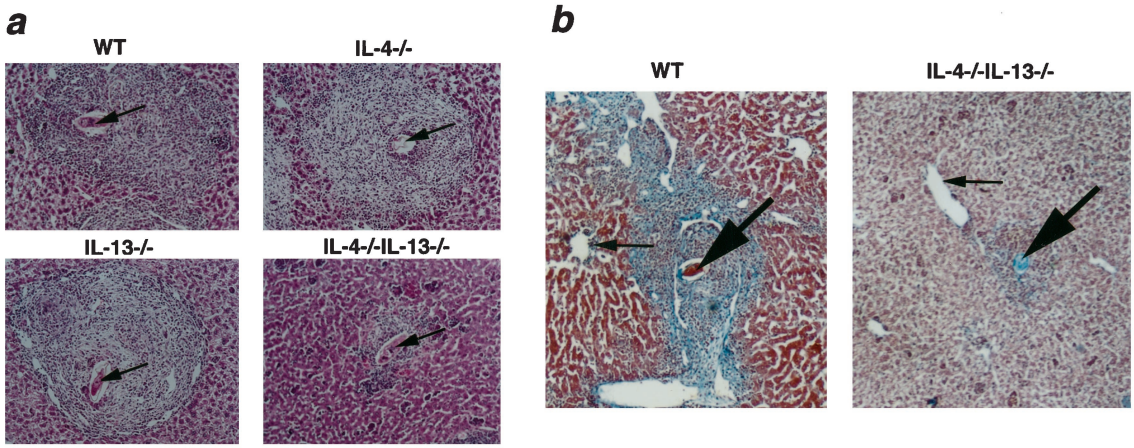

FIGURE 2. Hepatic pathology in IL-4-deficient, IL-13-deficient, IL-4/13-deficient, and wild-type mice during *S. mansoni* infection. *a*, Haematoxylin- and eosin-stained sections of livers from infected mice showing the granulomatous response surrounding a parasite egg (arrow). Original magnifications, ×100. *b*, Martius Scarlet Blue staining of sections of livers demonstrates the absence of fibrosis (blue staining) in IL-4/13-deficient mice compared with wild-type mice. The large arrow identifies a single egg and the small arrow identifies deposition of collagen around portal tracts. Original magnifications, ×40.

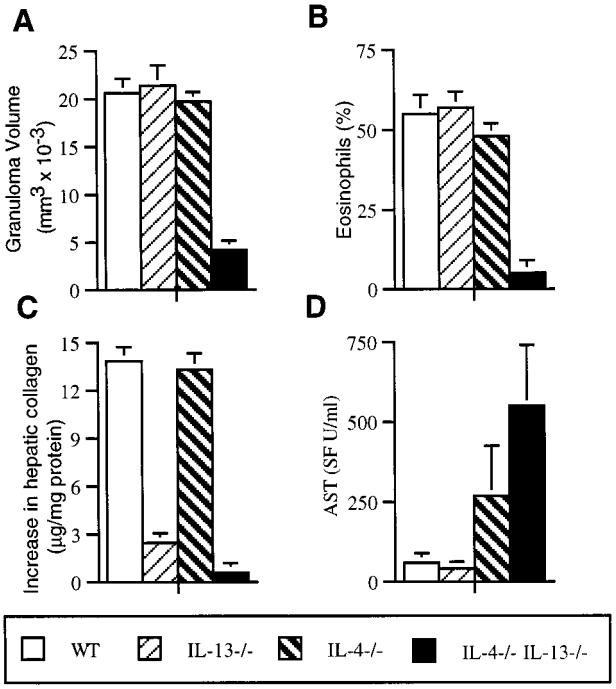

FIGURE 3. Quantification of hepatic pathology in IL-4-deficient, IL-13-deficient, IL-4/13-deficient, and wild-type mice during *S. mansoni* infection. Mice were acutely infected with 100 cercariae and terminated on day 45 after infection. *A,* Measurement of the volume of the granulomas surrounding individual eggs in the livers of infected mice. *B,* Enumeration of eosinophils, expressed as a percentage of total cells, within the granulomas. *C,* Analysis of the increase in hepatic collagen as a result of schistosome infection. *D,* Measurement of plasma levels of aspartate aminotransferase (AST) as an indicator of hepatocyte damage. All data are presented as group mean and SD. All pathological measurements were performed double-blind. Pathological parameters were measured in three separate acute infections (>6 mice per group), with consistent results obtained between experiments.

mice, although there were sporadic polymorphonuclear leukocyte infiltrations (primarily neutrophils) and foci of necrosis throughout the hepatic parenchyma (data not shown).

IL-4 but not IL-13 has a distinct role in intestinal function during schistosome infection

Intestinal pathology is a feature of schistosome infections of humans and mice. During *S. mansoni* infection, the intestine is subject to the insult of eggs laid by the adult worms in the mesenteric venules. These eggs must then translocate across the intestinal wall to the gut lumen for excretion in the feces. Examination of the gastrointestinal tracts from the infected mice revealed marked distension and inflammation of the ileum, but not the colon, in the IL-4/13-deficient and IL-4-deficient mice (data not shown). In contrast, the intestines of IL-$13^{-/-}$ mice were comparable to wild-type animals. The intestinal inflammation observed in the IL-4/13-deficient and IL-4-deficient mice correlated with dramatically impaired parasite egg excretion from the intestine (Fig. 4*A*), leading to an accumulation of eggs in the intestinal wall (Table I). The limited granulomatous response surrounding eggs in the ileums of IL-$4^{-/-}$ and IL-4/$13^{-/-}$ mice was characterized by limited eosinophil infiltration, $<1 \times 10^6$ eosinophils per gram of intestine; whereas in both wild-type and IL-$13^{-/-}$ mice there was marked intestinal eosinophilia, $>10 \times 10^6$ eosinophils per gram.

Alterations in the physiological functions of the intestine may represent a pathological consequence of intestinal inflammation. In particular, the integrity of the gut as a barrier may become compromised leading to systemic leakage of intestinal contents and endotoxemia. Analysis of LPS in the plasma of the infected mice demonstrated ~20-fold greater levels of LPS in the circulation of IL-4-deficient and IL-4/13-deficient mice compared with levels in wild-type and IL-$13^{-/-}$ mice (Fig. 4*B*). The levels of systemic LPS in the IL-$4^{-/-}$ or IL-4/13-deficient mice are comparable to circulating endotoxin levels in mice suffering from acute endotoxemia (36). In support of this conclusion, proliferation responses to cecal bacteria, by splenocytes or mesenteric lymph node cells derived from these mice, were substantially elevated (data not shown). Furthermore, splenocytes from IL-4-deficient and, even more markedly from IL-4/13-deficient mice, produced highly elevated levels of TNF-α and NO in response to LPS (Fig. 4*C*). Thus, as reported previously, IL-4 represents an important factor in the response to *S. mansoni* infection (37). However, the additional absence of IL-13 exacerbated the intestinal pathology, the associated elevation in systemic LPS leakage, and the increase in TNF-α and NO production (Fig. 4, *B* and *C*), indicating that IL-13 can also modify this immune response.

In many models of gastrointestinal inflammation, there is an alteration in the normal cytokine repertoire of the intestine (38). To examine the cytokine profile elicited in the intestines of the cytokine-deficient animals, ileum-derived $CD4^+$ lamina propria T cells from infected mice were examined using intracellular cytokine staining. Schistosome-infected wild-type and IL-$13^{-/-}$ mice had 10–15% IL-5-positive $CD4^+$ lamina propria T cells, with <5% of cells producing IFN-γ, indicative of a Th2-like phenotype in the intestines of infected mice (Fig. 4*D*). In contrast, $CD4^+$ T cells from the lamina propria of both the IL-$4^{-/-}$ and IL-4/13-deficient mice had 3-fold higher frequencies of IFN-γ-producing cells, with no IL-5-positive $CD4^+$ T cells detected (Fig. 4*D*), typical of a Th1-like response. The absence of Th2 cells in the lamina propria of IL-4- and IL-4/13-deficient mice was reflected by the virtual absence of eosinophils in the ileums of these mice (see above).

Systemic responses

To determine how the absence of IL-4, IL-13, or IL-4 and IL-13 together influenced the development of cytokine responses to infection, we isolated splenocytes from infected mice 45 days postinfection (before high mortality in the IL-4/13-deficient population) and assessed cytokine production following restimulation in vitro with soluble schistosome egg Ags. Wild-type animals exhibited a type 2 cytokine response with elevated IL-4, IL-5, IL-10, and IL-13 production and limited expression of IFN-γ (Fig. 5). A similar profile was observed in the analysis of IL-13-deficient mice, with the exception that IL-13 was not detected (Fig. 4). IL-4-deficient mice developed a diminished type 2 cytokine response, with limited IL-5, IL-10, and IL-13 being produced and a marginal (~2-fold) increase in IFN-γ production compared with wild-type animals (Fig. 5). In contrast to the single cytokine-deficient animals, IL-4/13-deficient mice developed a type 1 cytokine dominated response, with a 10-fold increase in the secretion of IFN-γ and negligible production of type 2 cytokines (Fig. 5).

While IL-13-deficient mice had normal IgE and IgG1 isotype responses to infection, IL-4-deficient mice exhibited lower levels of IgE and IgG1 and increased IgG2a (data not shown). IL-4/13-deficient mice had undetectable levels of parasite Ag-specific IgE but highly elevated production of IgG2a (data not shown), in keeping with their enhanced expression of IFN-γ.

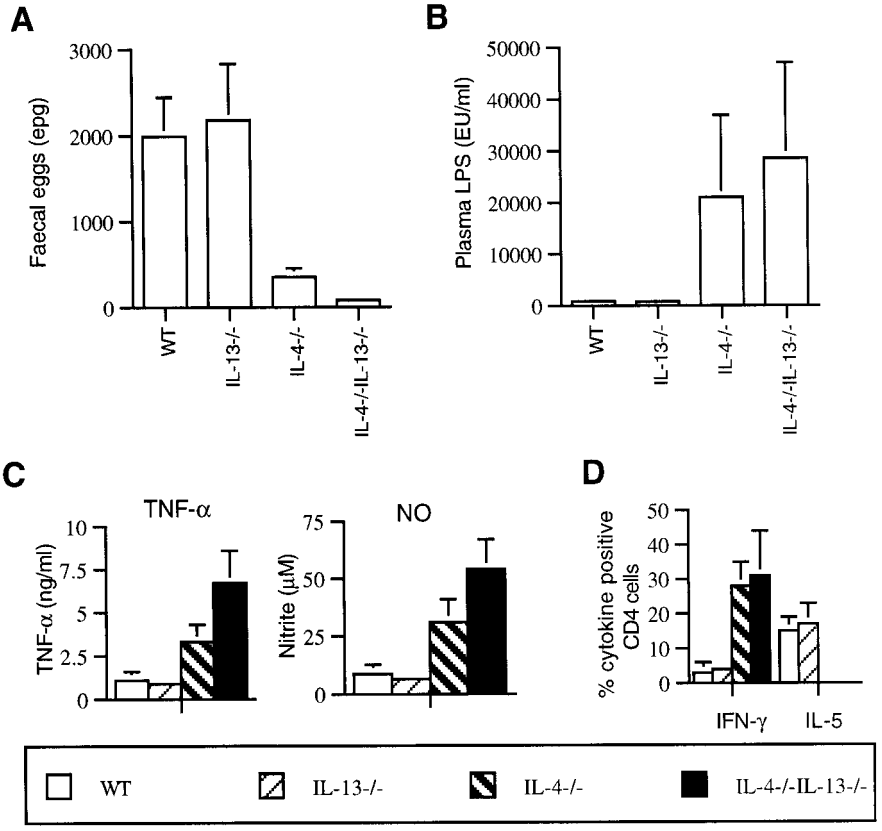

FIGURE 4. Intestinal pathology and systemic responses in IL-4-deficient, IL-13-deficient, IL-4/13-deficient, and wild-type mice during *S. mansoni* infection. Mice were acutely infected with 100 cercariae and terminated on day 45 after infection. *A*, Fecal samples were collected, and the number of eggs excreted (eggs per gram feces) was determined. Data are means and SD from six to eight mice per group. *B*, The state of endotoxemia was determined by measuring LPS levels in the plasma of infected mice. *C*, Splenocytes from mice that had been infected for 45 days were stimulated in vitro with LPS (1 μg/ml), and the production of TNF-α and NO was determined. Data are means and SD from triplicate cultures. Similar results were obtained in three separate experiments. *D*, Analysis of the frequencies (percentage) of $CD4^+$ lamina propria cells that stained for IFN-γ or IL-5. Lamina propria cells from the ileums of two mice were pooled, and values are mean percentages plus SD obtained from three separate experiments.

Discussion

This study demonstrates clear differences in the functions of these closely related cytokines in mediating Th2 cell responses to *S. mansoni* infection. The enhanced survival exhibited by the IL-13-deficient mice indicates that removal of IL-13 function can produce a beneficial effect on the outcome of infection, while the absence of IL-4 is detrimental. The improved prognosis in the IL-13-deficient mice correlated with a reduction in the expression of collagen and a resultant decrease in hepatic fibrosis. These data demonstrate that IL-13 has a unique role in hepatic fibrosis. A profibrotic role for IL-13 has also been shown in mice with targeted pulmonary expression of IL-13 transgenes, with these animals developing subepithelial airway fibrosis (39). More recently, a direct role for IL-13 in hepatic fibrosis during murine schistosome infection has also been demonstrated (25).

IL-4-deficient animals had normal levels of hepatic collagen deposition, whereas the doubly deficient mice exhibited a more profound reduction in collagen levels than the IL-13-deficient animals, indicating an additive effect of IL-13 and IL-4. The lower levels of hepatic collagen in IL-4/$13^{-/-}$ mice relative to IL-$13^{-/-}$ animals may reflect the elevated IFN-γ in double-deficient mice; IFN-γ has been shown to reduce hepatic fibrosis in murine schistosome infection (40). However, it is evident that IL-13 is the primary cytokine responsible for fibrosis. These data clarify the results reported for schistosome infections of STAT6- and IL-4R-deficient animals in which collagen deposition was found to be

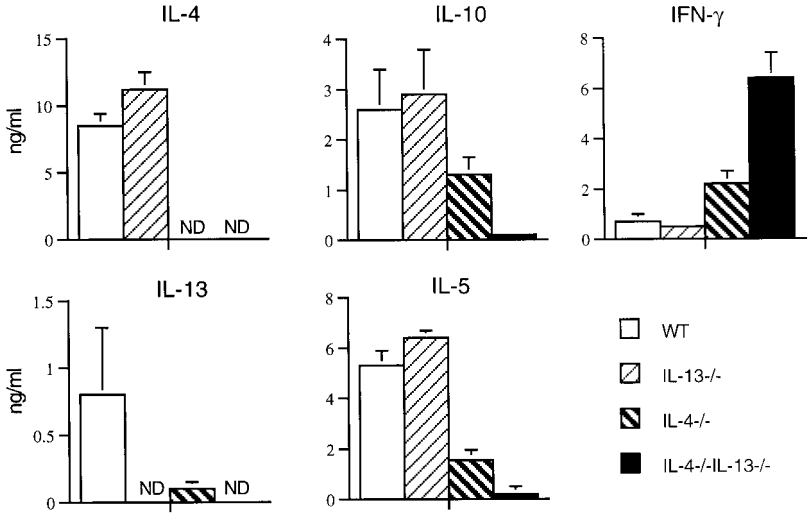

FIGURE 5. Parasite egg Ag-specific production of IL-4, IL-5, IL-10, IL-13, and IFN-γ by spleen cells from IL-4-deficient, IL-13-deficient, IL-4/13-deficient, and wild-type mice infected with *S. mansoni*. Mice were acutely infected with 100 cercariae and terminated on day 45 after infection. Data are the mean levels and SD of cytokines detected in triplicate cultures. Comparable data were obtained from four separate experiments. ND, Not detected.

Table II. *Summary of the consequence of* S. mansoni *infection of wild type, IL-13-deficient, IL-4-deficient, and IL-4/13-deficient mice*

	Liver				Intestine				Systemic		
	Gr[a]	Eo[b]	Fibrosis	Hepatocyte damage	Egg excretion	Eo[b]	Th1/Th2	Pathology	Endotoxemia	Mortalities[c] (%)	Th1/Th2
Wild type	+	+	+	−	+	+	Th2	−	−	5–10	Th2
IL-13$^{-/-}$	+	+	−	−	+	+	Th2	−	−	0	Th2
IL-4$^{-/-}$	+	+	+	+	−	−	Th1	+	+	80–100	Th1
IL-4/IL-13$^{-/-}$	−	−	−	+	−	−	Th1	+	+	85–100	Th1

[a] Gr, Granulomatous inflammation.
[b] Eo, Tissue eosinophilia.
[c] Mortalities are expressed as percentage (ranges) of mice dead by 56 days after an acute infection.

reduced (22, 23) and IL-4-deficient animals in which collagen responses were normal (41). Because periportal fibrosis is a major cause of hepatic pathology in human schistosomiasis (42), regulation of IL-13 activity to limit collagen formation and deposition may have therapeutic implications. Furthermore, the evidence described here for IL-13 acting as a fibrogenic agent highlights the importance of assessing its role in other fibrotic pathologies associated with type 2 cytokine responses, in particular asthma.

Obvious demarcation of cytokine function is demonstrated by the high mortality rates observed in the IL-4-deficient population. These animals display prominent intestinal damage resulting from an inability to regulate the translocation of the parasite egg across the intestinal wall to the gut lumen. Our data extends earlier observations implicating IL-4 having a potential protective role in schistosome infection (37). It is known that IL-4 can directly regulate various physiological activities of the intestine (43), and alterations in these processes in IL-4-deficient mice may account for the inability of parasite eggs to transverse the intestine in these mice. In the absence of IL-4 (IL-4-deficient or IL-4-/13-deficient mice), parasite eggs are not excreted efficiently and are trapped in the intestine, causing intestinal inflammation leading to systemic LPS leakage. In contrast, the IL-13-deficient mice do not develop intestinal inflammation in response to infection. As the livers of schistosome-infected mice are more susceptible to endotoxins (44), leakage of LPS will exacerbate liver damage and ultimately result in the death of the mouse. Because IL-4 and IL-13 have both been shown to suppress proinflammatory responses, the combined absence of both cytokines may result in unregulated expression of inflammatory mediators (45). Thus, the combined liver-intestine insult in a proinflammatory environment may account for the hepatocyte damage observed in IL-4-deficient and IL-4/13-deficient animals.

In the absence of IL-4, the cytokine response during schistosome infection is changed from a type 2 phenotype to a more type 1-dominated response. However, as reported previously, IL-4$^{-/-}$ mice do produce type 2 cytokines during infection (23, 37, 41, 46). However, while IL-13-deficient mice retain a Th2 phenotype in response to infection, the doubly deficient animals verify that IL-13 does play an additive role with IL-4 in suppressing the emergence of a type 1 response. Thus, the IL-4/13-deficient animals display a highly polarized Th1-like phenotype. However, it is clear that IL-4 is the dominant factor in this process.

Despite the formation of the schistosome granuloma being type 2 cytokine dependent, it has recently been highlighted that type 2 cytokine responses have a protective role in schistosome infection (34). Thus, in a number of different mouse models (IL-4-deficient mice; schistosome egg-tolerised mice; CD4$^+$ T cell-depleted mice) there are marked mortalities during schistosome infection that are associated with diminished type 2 cytokine responses (29, 35, 37). In this study, we further demonstrate that the protective role of type 2 responses is particularly apparent in the intestines of infected mice. During infections of normal mice, the process of egg translocation through the intestinal wall is associated with local granulomatous inflammation, eosinophilia, and a Th2 response (Fig. 4*D*, above). In contrast, in mice that fail to excrete parasite eggs (Refs. 29 and 35, this study), there is intestinal inflammation. The intestinal pathology in these mice is associated with a Th1-dominated response in the ileum and impaired recruitment of eosinophils to intestine. This implicates that type 2 cytokine responses, in particular intestinal eosinophilia, reduce intestinal damage elicited during schistosome infection.

In this study, cytokine-deficient animals have enabled us to decipher the individual effects of IL-4 and IL-13 and to assess the result of combined IL-4/13 disruption on the pathology of infection. These results are summarized in Table II, and demonstrate a clear demarcation of function for IL-4 and IL-13 in the development of pathology. It is clear that inhibiting IL-13 results in an improved prognosis that is characterized by the generation of a normal Th2 response, but an attendant decrease in hepatic fibrosis and an associated reduction in mortality. In contrast, IL-4-deficient mice display depressed Th2 responses, continue to deposit hepatic collagen, and succumb to severe intestinal inflammation resulting in endotoxemia and death. Analysis of the doubly deficient animals shows that combined blocking of both IL-4 and IL-13 is extremely detrimental, resulting in an even more severe phenotype than that displayed by the IL-4-deficient mice. IL-4/13-deficient animals demonstrate that the beneficial effects of removing IL-13 in isolation are overcome by the pathological consequences of removing IL-4 and highlight the additive roles that both of these cytokines play in suppressing the development of Th1 responses. These results indicate that IL-13 is a key target for therapeutic intervention.

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